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THE USE OF MULTIPLE-ELEMENT BEVERAGE ANTENNA ARRAYS FOR HF TRANSMISSION

by

G.E. Moss, N. Muirhead and R.W. Jenkins

DEPARTMENT OF COMMUNICATIONS
MINISTÈRE DES COMMUNICATIONS

CRC REPORT NO. 1318

This work was sponsored by the Department of National Defence, Research and Development Branch under Project No. 32B42.

CANADA

OTTAWA, JULY 1978

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ABSTRACT

The potential of multiple-element Beverage arrays for HF transmissions has been explored, and practical techniques of power division, antenna coupling, and grounding developed. The effect of interactions between elements, which limits the efficiency achievable by such arrays, has been determined for element heights of the order of 2m. The gains observed for an experimental array, as a function of frequency, elevation, and azimuth, were found to agree with that predicted theoretically, except at elevation angles above the pattern maxima; this discrepancy may be explainable in terms of a multi-layered earth which was not considered by the theory. It is found that the Beverage antenna array presents an inexpensive alternative for both transmitting and receiving, on long-range point-to-point communications circuits. An example of a transmitting Beverage array developed for such application is presented; recommendations for the design and implementation of such arrays are given.

1. INTRODUCTION

The basic configuration of a Beverage antenna is illustrated in Figure 1. It consists of a horizontal wire, a small fraction of a wavelength above the ground, terminated at the far end by a resistance equal to its characteristic impedance. At the feed end, the signal may be coupled into the antenna via a matching transformer. The wire and ground combination acts as a radiating transmission line, with a current wave travelling down the wire (and through the ground) with a speed only slightly less than the free-space electromagnetic wave velocity. A vertically polarized wave is transmitted in

the forward directions, preferentially at low elevation angles where the phase of the radiated field remains close to that of the current-wave.

The utility of the Beverage antenna for reception at HF has been demonstrated in a previous report[1], referred to herein as "reference 1". Features which make this antenna particularly useful for certain receiving applications are its high directivity, broad-band response, low-elevation-angle pattern, and the relatively low cost of installation and maintenance. In addition to these desireable features, however, the Beverage antenna has been found to possess a low efficiency, typically of the order of 1% at high frequencies. The low efficiency can be readily overcome for reception by the use of a low-noise preamplifier, but it poses problems for transmission.

One promising technique for increasing the efficiency of transmission is the use of several closely-spaced antennas in lieu of a single antenna. Such a technique was originally employed at VLF[2] and has been previously utilized for Beverage antennas[3]. For the ideal approximation of non-interacting, closely-spaced antennas, the power available is divided equally amongst the separate elements while the resultant field amplitudes are added in phase; thus the efficiency increases in proportion to the number of elements used. In practice this argument breaks down when interaction occurs between the closely spaced elements. The question is, "how closely can antenna elements be spaced before interactions significantly limit their combined efficiency?" This question has been considered for the case of short vertical dipoles[3]; however, to our knowledge, no systematic theoretical or experimental treatment has appeared in the literature for horizontal or travelling-wave antennas, such as the Beverage antenna.

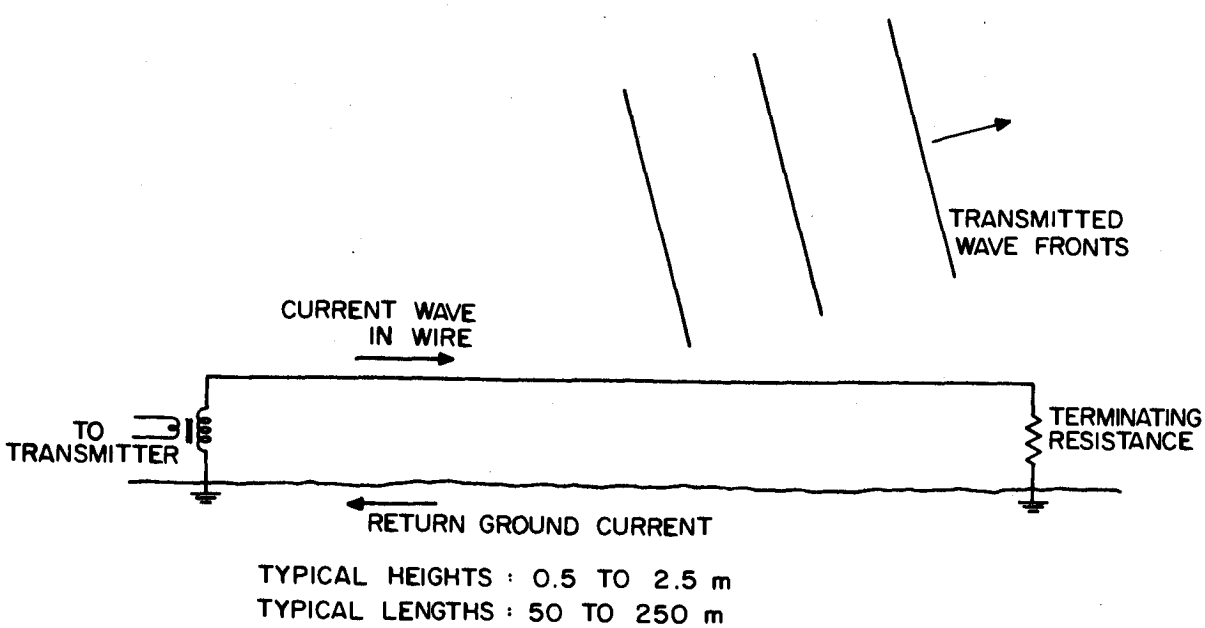


Figure 1. Side view of the Beverage antenna, illustrating the principles of operation.

The thrust of the CRC work has been to explore the potential of multiple-element Beverage antenna arrays for various HF transmission requirements, and to develop practical techniques of power division, antenna coupling, termination, and grounding. The remainder of this report presents our findings, and gives an example of a transmitting Beverage antenna that was developed for a specific communications circuit. Recommendations for use in the design and implementation of transmitting and receiving Beverage arrays are given, so that this report, together with reference 1, form a reasonably complete set of references for anyone considering the implementation of these antennas at HF.

2. DEVELOPMENT

2.1 SINGLE-ELEMENT STUDIES

2.1.1 Antenna Height

From the theoretical studies contained in reference 1, it can be seen that the antenna efficiency is increased as the height is raised, at least for heights less than one-eighth wavelength. As the frequency range of interest lay between 3 and 25 MHz, it was felt that a reasonable compromise between high single-element gain and ease of construction would be an antenna of height 6 feet (1.8 m). The majority of the studies reported here are restricted to this value.

2.1.2 Attenuation Constant

A current wave travelling along a Beverage antenna suffers attenuation as a result of ohmic losses in the ground, and to a lesser degree radiation losses. Increasing the length of a Beverage antenna might be expected to increase its gain at low angles. However attenuation imposes a natural limit to the increase in gain that can be achieved in this way. The attenuation length is normally defined as the length required for the current wave to be reduced to 1/e of its original value, and very little improvement in gain would be achieved by extending an antenna beyond two such lengths.

One step in the present development work was to determine the attenuation length, for a 500 foot (151 m) long antenna installed at a test site, near CRC, using frequencies spanning the HF spectrum. A current probe was employed to measure the AC current along the Beverage element relative to that at the feed point, while maintaining a fixed transmitter power into the antenna.

A monotonically decreasing current was observed, except near the termination end of the antenna where a series of maxima and minima were seen to occur at near-half wavelength intervals. This suggested a standing wave which probably resulted from the reflection of part of the current wave at the termination. For the greater portion of the Beverage antenna, the current was found to decrease approximately exponentially with length, and characteristic attenuation lengths could be derived at all frequencies. The values found are given in Table 1.

TABLE 1

Observed Attenuation Length as a Function of Frequency

Frequency (MHz)	Attenuation Length (m)
3.1	113 ± 6
5.0	70 ± 4
9.0	50 ± 3
15.0	42 ± 2
25.0	39 ± 4

The corresponding attenuation constants are plotted in Figure 2. Also plotted is the theoretical best-fit curve obtained by varying the ground parameters for the computer program given in reference 1. The assumed dielectric constant (ε) was observed to have the major influence on the theoretical attenuation constant at the lower frequencies, while the conductivity (σ) determined the value for the higher frequencies. The best-fit theoretical curve can be seen to be in good agreement with the measured values. The ground parameters thus derived for the test site were $\varepsilon = 18 \pm 2$, and $\sigma = 10^{-3} \left(^{+10^{-3}}_{-.5\times10^{-3}}\right)$ mhos/m.

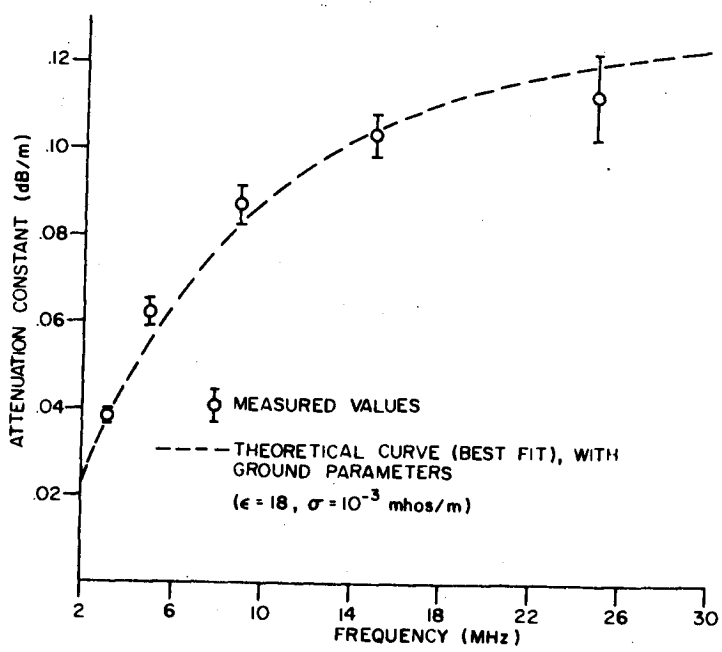


Figure 2. Attenuation constant as a function of frequency for a 1.83 m high Beverage antenna at the CRC test site

2.1.3 Matching Considerations

For an antenna to maintain a low reflected-power level over the frequency range of interest without the aid of specially-switched matching networks, it is important that its characteristic impedance be constant and real. The Beverage antenna should, on the basis of theory, exhibit this behaviour, and so the feed transformer and terminating resistance are normally set to a single characteristic value. However, in practice the physical arrangements used for feeding and terminating this antenna are observed to affect its characteristic impedance and therefore reflected power. This is of special concern for the case of transmitting antennas, as it can significantly affect the power dissipation requirements of the transmitter.

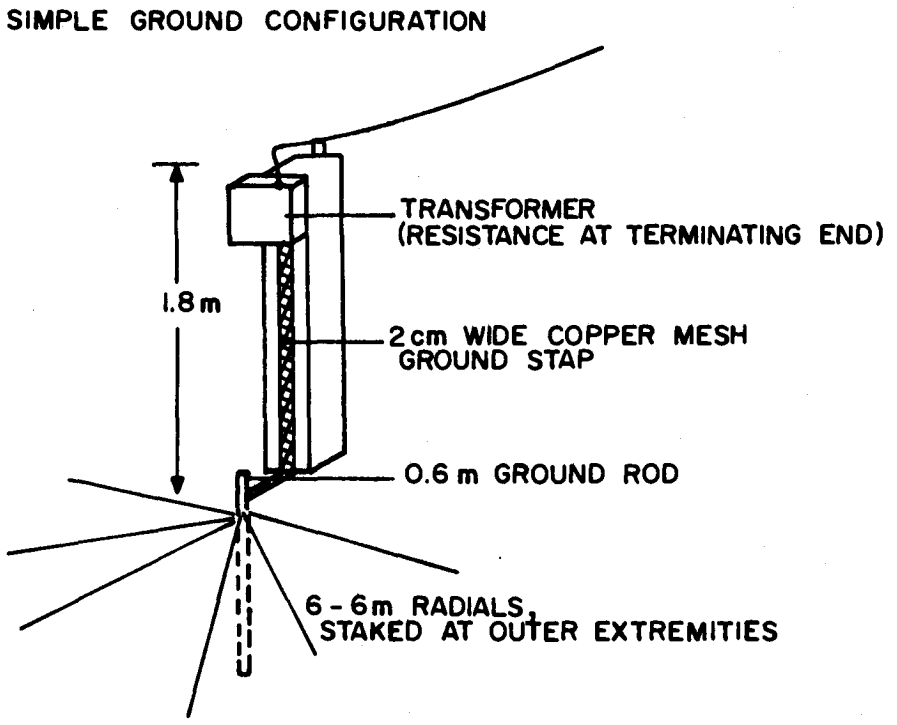
Various systems of grounding at the feed and termination points were tried, on a 1.8 m high, 151 m long antenna at the test site, in order to evaluate their effect on the characteristic impedance and reflected power.

"Launchers" have been found by the USAF Rome Air Development Center[4] to be useful in low height ($\lesssim$ 1 m) receiving installations for reducing reflected power at the feed and termination ends of the antenna. The use of launchers was attempted at CRC as a means of feeding and terminating Beverage antennas. The system used is illustrated in Figure 3a. The results were compared with those of a more simple grounding system consisting of a single ground strap connected to six ground radials and a ground rod, also illustrated in Figure 3a.

Figure 3b shows the characteristic impedance, measured for the two grounding configurations by replacing the feed transformer by a vector impedance meter. Both configurations produce impedances within 30% of the near-constant theoretical value over the 2 to 32 MHz frequency range. However significant differences exist: The characteristic impedance amplitude for the launcher configuration was consistently less than the 500 ohm theoretical value, averaging approximately 450 ohms; in addition the phase was consistently more negative than the near-zero theoretical value. The impedance for the simple configuration remained close to 500 ohms amplitude below 15 MHz and zero phase below 20 MHz, but increased in amplitude and became negative in phase above these values.

Figure 3c gives the fraction of incident power reflected for the two configurations. For these measurements a power meter was installed on the transmitter side of the feed transformer. The feed transformer and terminating resistance were matched to 500 ohms for the simple ground configuration, and 450 ohms for the launcher configuration. As Figure 3c illustrates, the fraction of reflected power was generally lower for the simple ground configuration, as expected from the more-constant and non-reactive impedances observed for this configuration. The fraction of power reflected was observed to be nearly zero between 2 and 12 MHz, rising to 0.1 at 14 MHz for the launcher and 18 MHz for the simple ground, and finally to 0.35 at 30 MHz for both configurations.

The launcher configuration used in Figure 3a was as close to optimum as we could determine. Perturbations in this configuration from that of Figure 3a, such as moving the top of the launcher up, closer to the feed point, were observed to produce a poorer result.



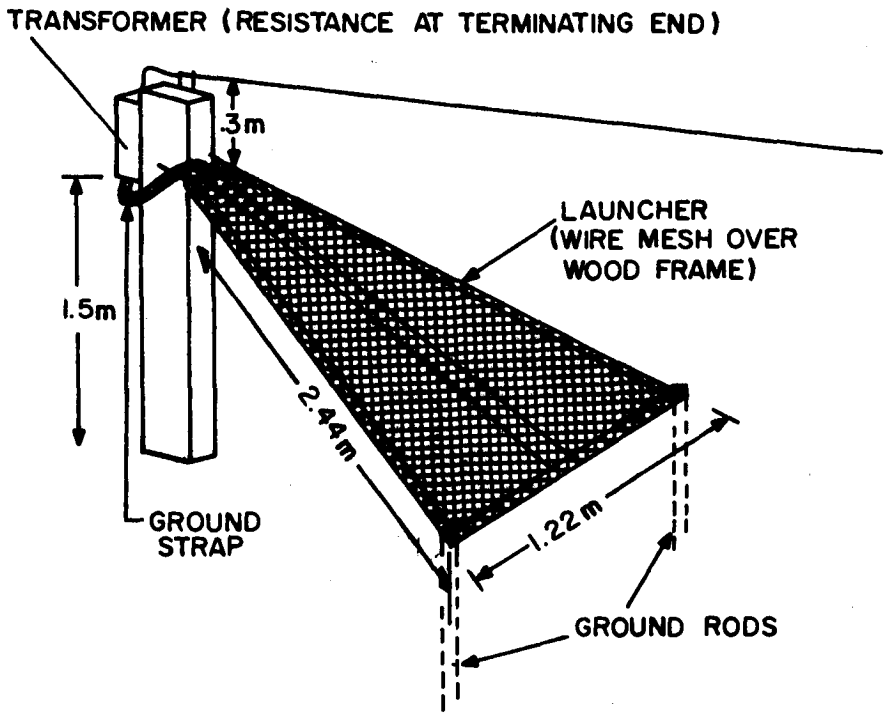


Figure 3a. "Simple" and "launcher" grounding configurations used in impedance and reflected power measurements

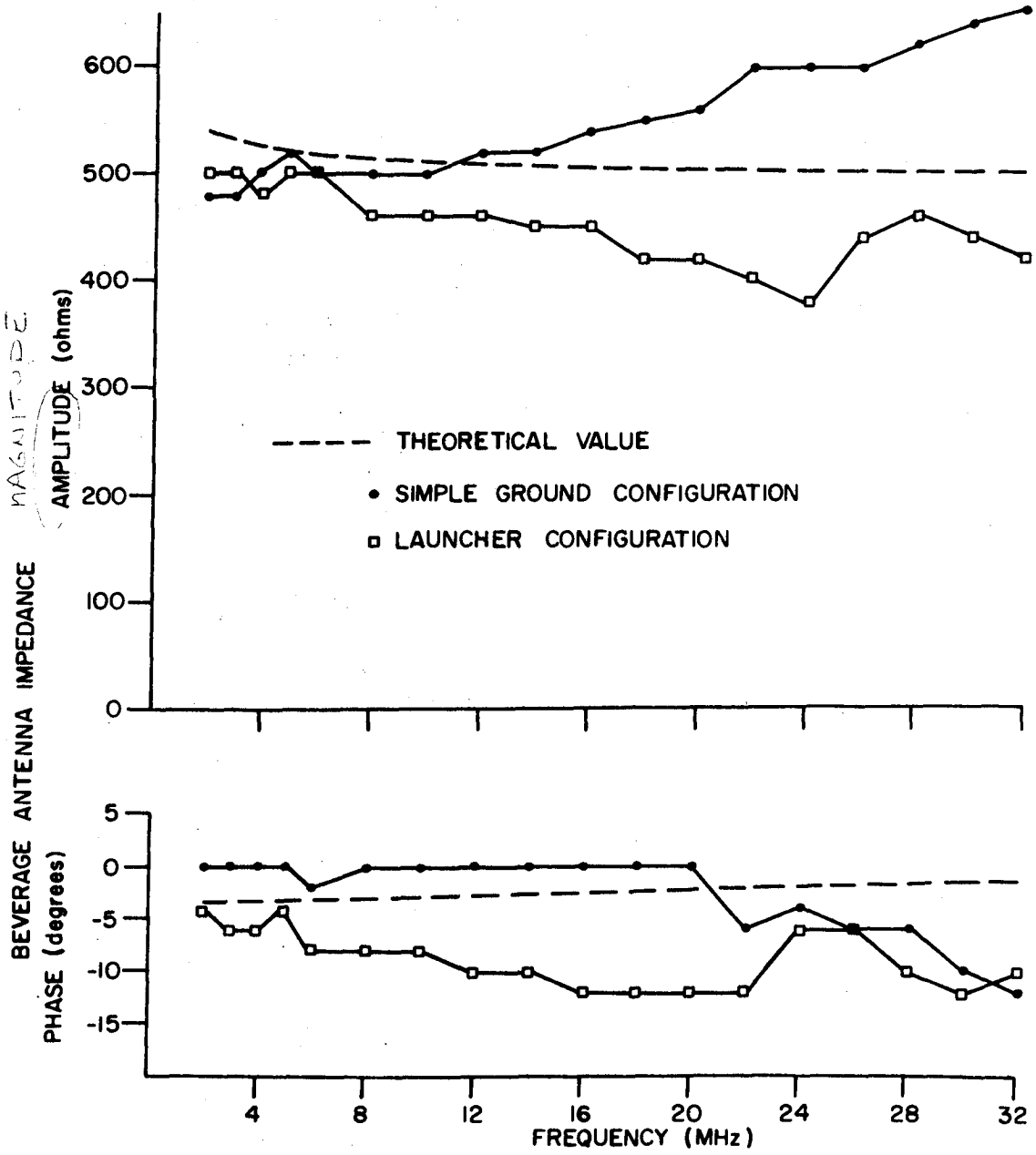


Figure 3b. Characteristic antenna impedance, as a function of frequency, for the simple and launcher grounding configurations.

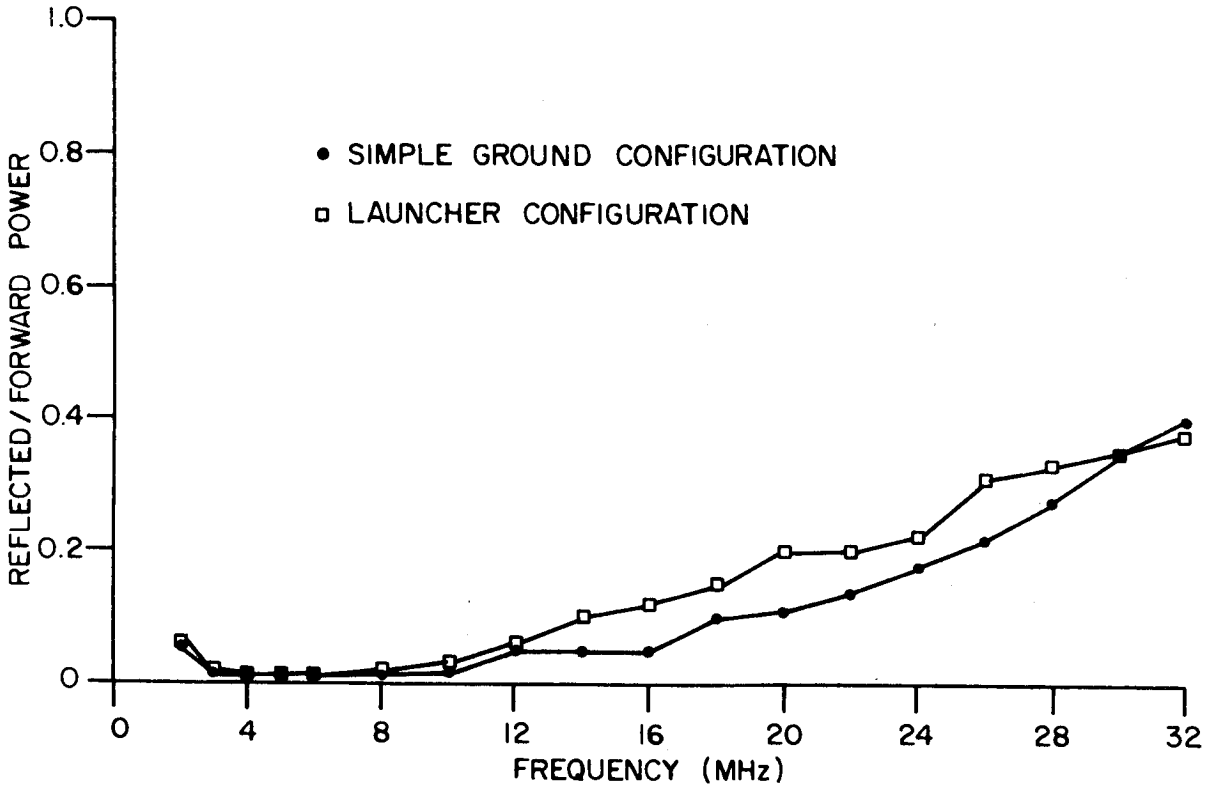


Figure 3c. Reflected to forward power ratio, for the simple and launcher grounding configurations.

Therefore for the case of the relatively high (1.8 m) Beverage antenna, the additional expense of launchers does not appear to be warranted. It should be noted, however, that a spot check for lower heights (~1.0 m) confirmed the RADC experience, indicating some reduction in reflected power with the introduction of launchers; thus for lower heights the use of this device appears worthy of consideration.

In addition to launchers, various systems of grounding were tried at the feed and termination ends of the antenna, in order to evaluate their effect on the antenna response and to develop appropriate grounding techniques. Ground radials were utilized in all systems as previous experience has shown the need for a good capacitive ground over poorly conducting soils. Three representative grounding systems are illustrated in Figure 4a. The measured characteristic impedances, as a function of frequency, were compared with the theoretically predicted values derived using the ground parameters determined from the attenuation measurements.

The results are illustrated in Figure 4b for the three grounding configurations. All three produced an impedance which remained constant within 12% of 500 ohms and non-reactive within 15° of phase, over the HF spectrum. The largest discrepancy for all configurations occurred at the higher frequencies, where the phases became more negative and the amplitudes larger.

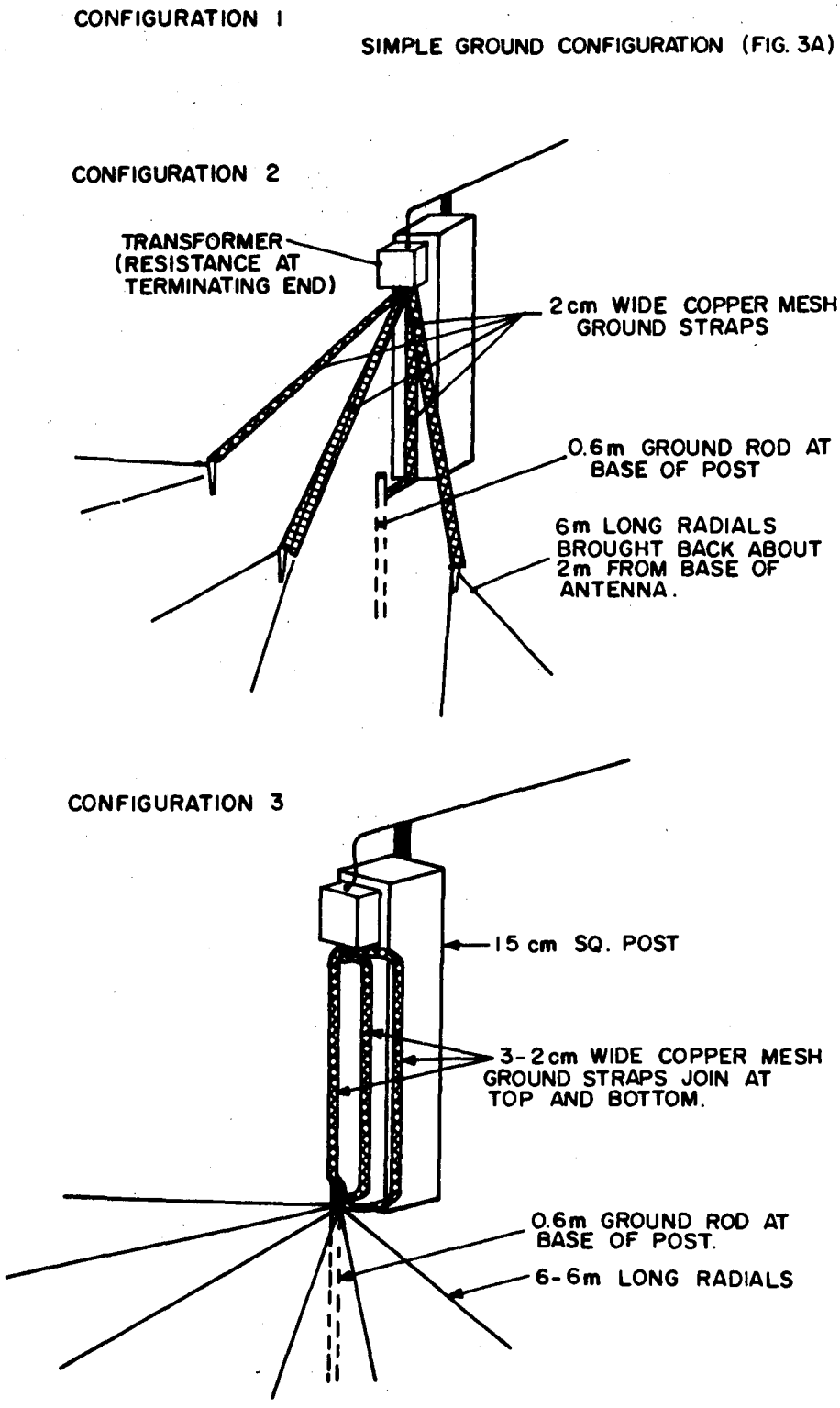


Figure 4a. Three grounding configurations evaluated in impedance measurements

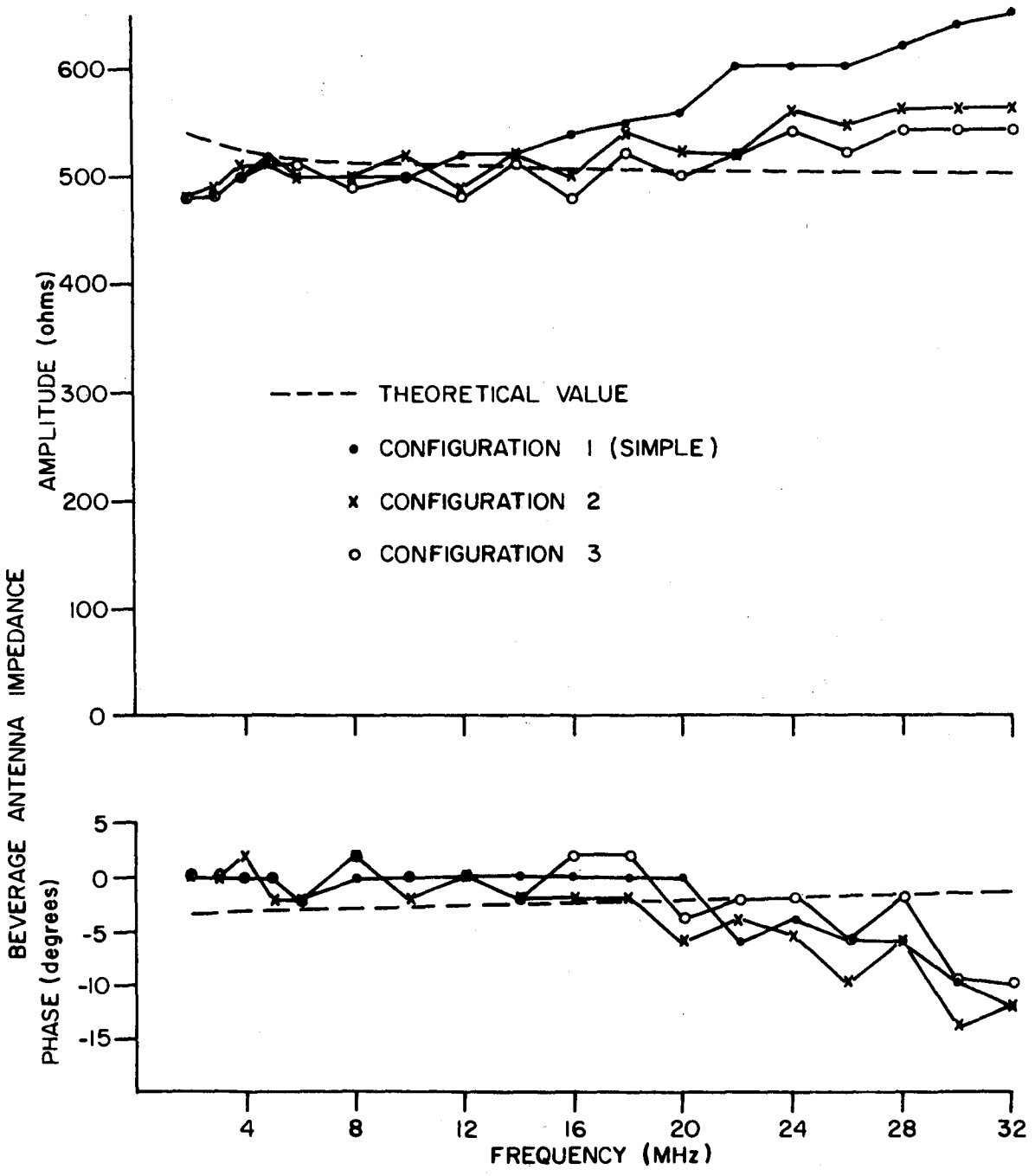


Figure 4b. Characteristic impedance as a function of frequency for the three grounding configurations of Figure 4a.

The results clearly demonstrate the good broad-band behaviour of the Beverage antenna. The lack of precise agreement with theory and the differences in impedance between various grounding configuration are an indication of the significant role that specific feeding and terminating techniques play in determining the behaviour of this antenna. The poorest result was obtained for the simple configuration (no. 1) while the best result was noted for the broader 3-strap connecting arrangement running vertically down the support posts (no. 3).

2.2 MULTIPLE ELEMENT STUDIES

2.2.1 Effect of Spacing

The dependence of antenna gain on inter-element spacing was determined experimentally for a two-element array, and the results used to predict the corresponding dependence for larger arrays. Although the measurements were made in the receive mode, the results are applicable to both transmitting and receiving arrays.

2.2.1.1 Two-Element Array

The experimental arrangement consisted of two 1.8 m high, 130 m long Beverage elements, erected parallel to each other in a wet clay field free of near-by radiators. The two elements were directed toward the Ottawa time standard (CHU) transmitter eleven km away. The received CHU signals from the two elements were delivered to a 2 to 1 power combiner by matched cables, and then to a pre-amplifier, linear receiver and digital voltmeter, from which the levels were recorded. Corresponding signals from a vertical whip antenna 700 m distant were simultaneously recorded, to facilitate removal of time fluctuations in the CHU transmitter power from the data. Measurements were made at each of the three CHU frequencies: 3.33, 7.335, and 14.67 MHz, using spacings from 0.9 to 26 m, on the combined signal from the two elements, and on the signals from each of the elements separately. Also, measurements were made for a single Beverage element. In addition, the characteristic impedance of one element in the presence of the other was measured, at frequencies near those of the signal measurements.

The results are summarized in Figures 5 and 6. Figure 5 shows the change in signal level (and therefore gain) that occurred as the two elements were brought together. The fixed-element values were taken relative to the single Beverage value (i.e. infinite spacing). It can be seen from these values that the presence of a second element at 26 m had negligible effect. The movable-element and two-element values displayed are those relative to 26 m. Figure 6 shows the characteristic impedance found, as a function of spacing; also shown is the value (500 ohms) for the terminating resistance and feed-transformer matching.

At a large separations, the two antennas can be expected to act independently; i.e., a zero dB change in gain from the single Beverage, for each of them. At extremely close separations they should behave as a single element when taken together, each element having half its original gain; i.e. a 3 dB decrease in gain for each element. The results of Figure 5 are consistent with these expectations: the elements behaved as independent

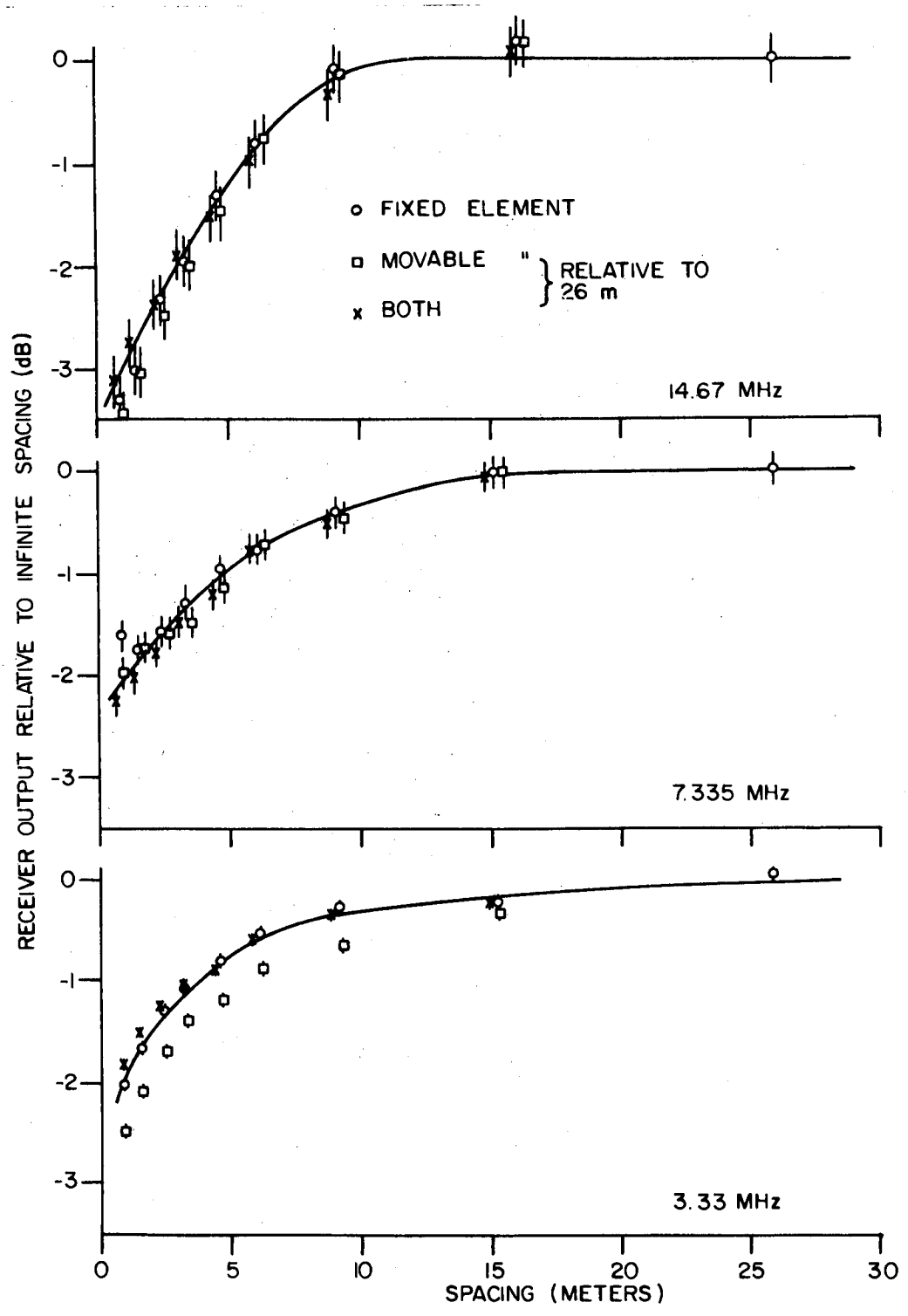


Figure 5. Receiver output for individual elements and elements taken together, for a two-element Beverage array, as a function of spacing between the elements. Levels taken are relative to either infinite spacing (single fixed element), or the largest measured spacing, i.e., 26 m (movable element and element pair). Smooth curves drawn through the points were used to compute the results in Figure 7.

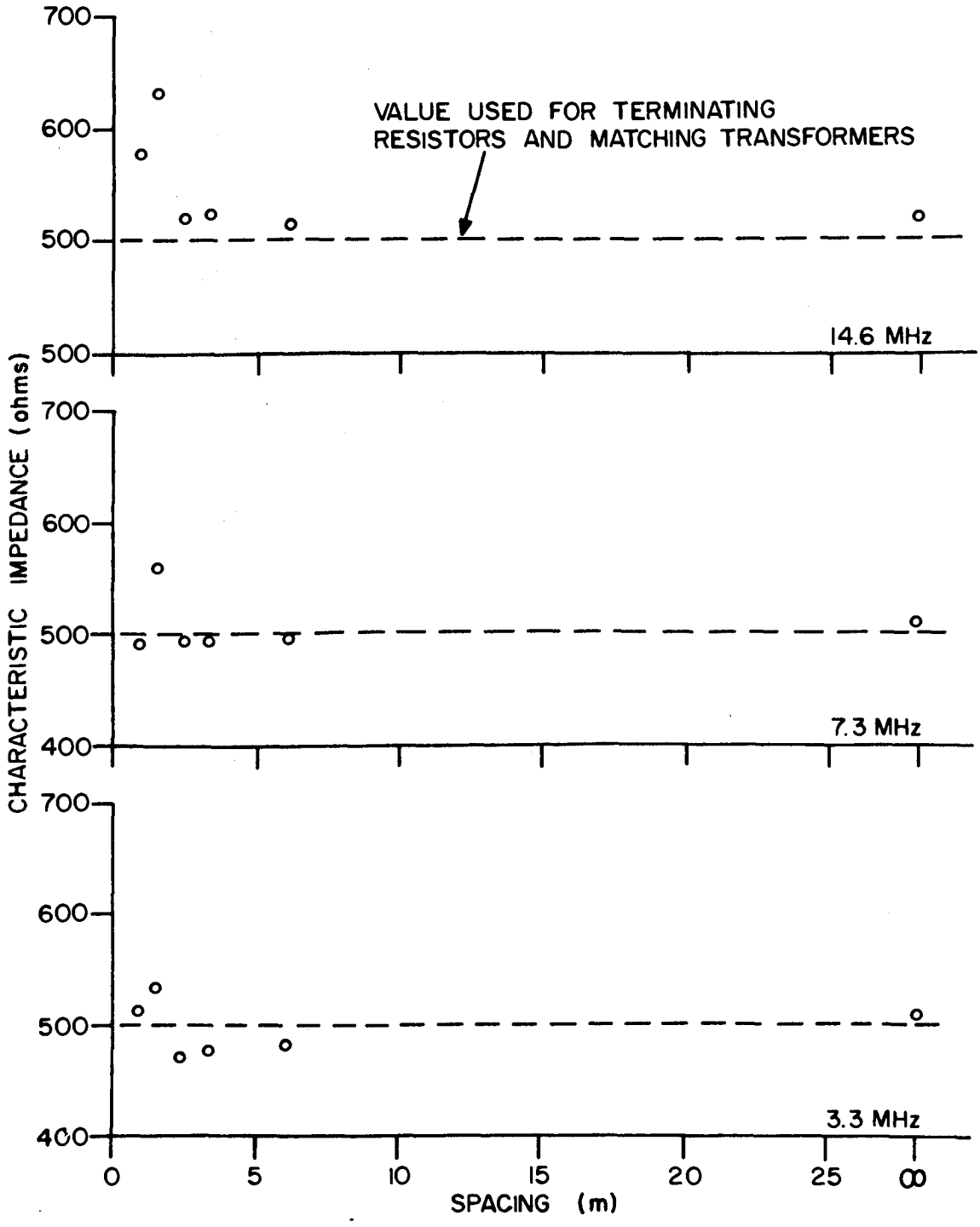


Figure 6. Characteristic single-element impedance for a two-element Beverage array, as a function of spacing between the elements.

antennas at separations greater than 10 m, and as the separation was reduced to 0.9 m, their combined behaviour approached that of a single-element antenna. At 14.67 MHz, the decrease in gain as the elements were brought together was observed to exceed 3 dB; this can be explained with reference to Figure 6, in terms of an impedance mismatch that occurred at spacings below 2 m and was most prominent at 14.67 MHz.

Some frequency differences are suggested in the effect of element spacing upon gain in Figure 5:

(i) the spacing at which interactions become noticeable is lowest for the higher frequencies; and

(ii) for close spacings, the interactions are stronger at the higher frequencies.

2.2.1.2 Larger Arrays

The results for the two-element array were extended to predict the effect of spacing on larger arrays; the concept of coupling constants was used for this purpose.

For a two-element array, where the elements are identical, the signal (i.e. current) I_2 in an element is given by

$$I_2 = I_1 + a(d)I_2 \tag{1}$$

where I_1 is the current that would be present in the absence of the second element. The term $a(d)I_2$ represents the current induced by the second element, where $a(d)$ is a coupling constant which is dependent on the spacing between the two elements and I_2 is the current in the second element (identical to the first element). The receiver output voltage V is proportional to the current I, so that the coupling constant can then be given in terms of receiver output voltage V, by

$$a(d) = 1 - (V_2/V_1)^{-1} \tag{2}$$

For a large array, with identical elements and uniform spacing d, neglecting end effects, each element can be considered to be a distance d from the two closest elements, 2 d from the two next closest elements, 3 d from the next two, and so on. The coupling constants between any two elements are the same as previously, they depend only on the distance between the two elements in question and not on the elements between them. Therefore equation (1) becomes in this case

$$I = I_1 + 2\,a(d)I + 2a(2d)I + 2a(3d)I + \ldots \tag{3}$$

The change in receiver voltage resulting from the inter-element coupling is then

$$V(d)/V_1 = \frac{1}{1 - 2\sum_k a(kd)} \tag{4}$$

The coupling constants a(d) were found from the voltage ratio V_2/V_1 curves given in Figure 5, using equation (2), and used to derive the corresponding voltage ratios $(V(d)/V_1)$ for elements within a large array as a function of spacing, using equation (4).

The power combiners in an array combine in-phase signals so that the powers add. Therefore, the power gain G in a fixed-aperture linear array with $n = \frac{1}{d}$ elements per unit aperture is proportional to $n(V(d)/V_1)^2$. This power gain is plotted as a function of n in Figure 7.

From Figure 7, the effect of interactions on limiting the gain achieved by adding elements is evident at all three frequencies, but is most prominent at the highest (14.67 MHz) frequency. The results indicate that at this frequency there is no advantage to be gained by increasing the number of elements per unit aperture beyond .17 elements/m, i.e. a separation of 6 m. The limiting is not as well-defined at the two lower frequencies, but the results still imply that there is little to be gained by increasing the density of elements beyond .17 elements/m.

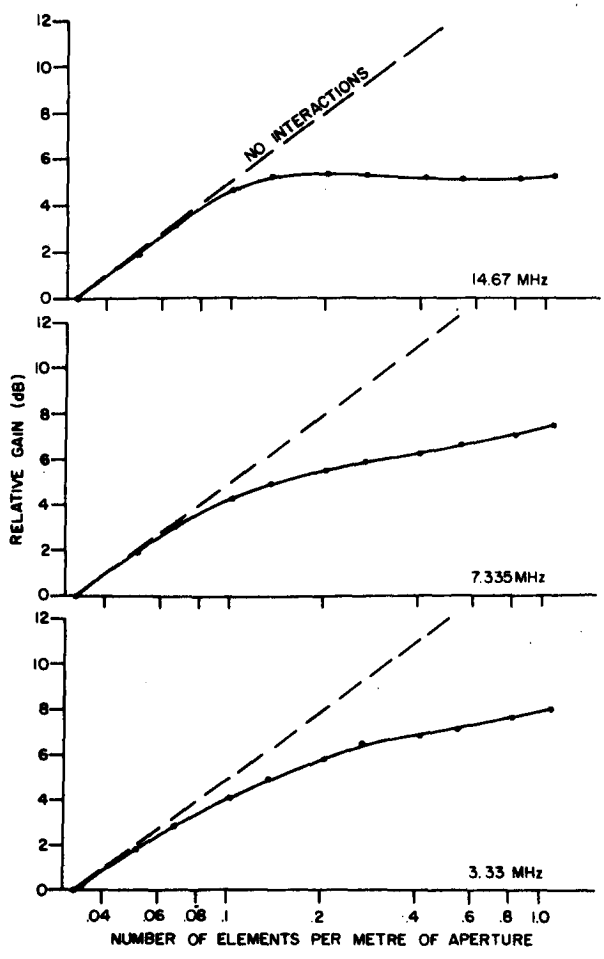


Figure 7. Relative gain, for a fixed-aperture Beverage antenna array of 1.83 m height, over wet clay (poor to average ground), as a function of the number of elements per unit aperature.

2.3 EXPERIMENTAL ARRAY

2.3.1 Description

Early in the work, an experimental transmitting Beverage array was constructed near CRC, in order to demonstrate the effectiveness of the Beverage antenna for transmission. The array is illustrated in Figure 8. It consisted of eight 1.8 m high, 151 m long Beverage elements arranged in pairs of two. Each pair was directly coupled to a matching transformer; the transformers were connected via coaxial cable to a 1:4 power divider.

The 1:4 power divider was developed at CRC especially for this application, for the 3-30 MHz range and powers up to 10 kW. This divider has recently been patented. Further details are given in the Appendix.

Grounding at the feed end was accomplished with the aid of a continuous wire mesh to which one output terminal of each matching transformer was attached. This mesh provided a good capacitive ground for the array. It was found that a similar continuous mesh at the termination end tended to reduce the gain, probably as a result of increased interaction between elements; therefore at that end, each element was terminated to a separate section of wire mesh.

The antenna was designed to handle 1 kW of transmitter power, and was used in channel evaluation trials on a long-path circuit (Ottawa-to-Alert, a distance of 4156 km), along with a nearby vertical log-periodic antenna with which it was compared. The performance, as determined from RTTY copy, was found to be as good or slightly better, with the Beverage transmitting array, than with the more costly log-periodic antenna.

2.3.2 Pattern Measurements

Antenna pattern measurements of the experimental array were made, using an airborne HF transmitter with the array in the receive mode, at 5.1, 9.3, and 15.1 MHz. A quarter-wave vertical whip antenna was erected nearby to provide an absolute calibration for these measurements at the two higher frequencies. The 5.1 MHz measurements were normalized to the theoretical pattern, derived as described later in this section, using the values below 20° elevation angle. The nearby vertical log-periodic antenna was also measured at this time. Details of the measurement technique are provided in a separate document[5] currently being prepared for publication. The pattern measurements were repeated for both summer (1 m high grass, damp ground) and winter (15 cm dense snow cover, partially frozen ground) with no change in the results.

Figures 9a and 9b give the observed elevation and azimuthal patterns, in dBi, for the experimental array. Table 2 lists some of the observed gain parameters. These results indicate that the Beverage array is well suited for use in long-range point-to-point communications circuits, both as a transmitting and receiving antenna; it has a good low-angle response, and high directivity (which reduces both susceptibility to interference and interference to others).

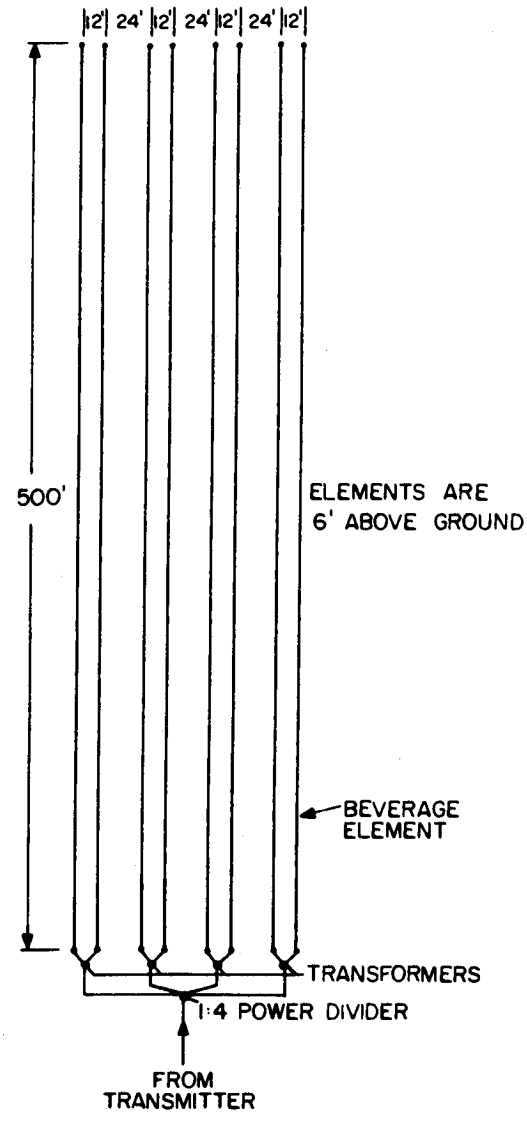


Figure 8. Plan view of experimental Beverage array

TABLE 2

Observed Gain Parameters for the Experimental Beverage Array

Frequency (MHz)	5.1	9.3	15.1
Maximum gain (dBi)	2.6**	4.5	7.5 (±1 dBi)
Elevation angle of maximum	15°	16°	14°
Elevation beamwidth*	24°	19°	12°
Azimuthal beamwidth*	33°	28°	17°

* at the 3 dB points;
** theoretical value used.

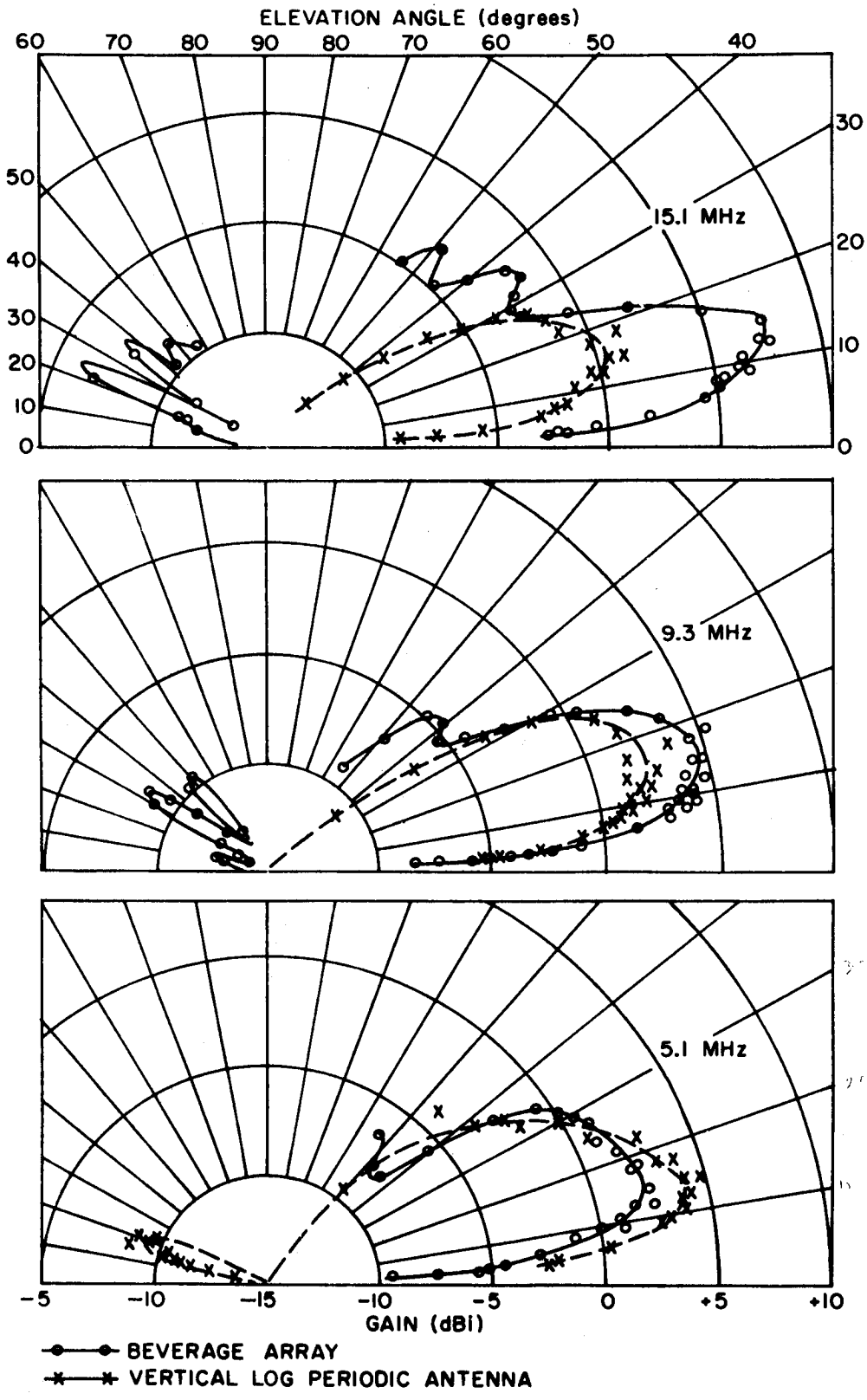


Figure 9a. Measured elevation patterns in dBi, at 5.1, 9.3, and 15.1 MHz, for the experimental Beverage array and a nearby vertical log-periodic antenna (Granger model 747V).

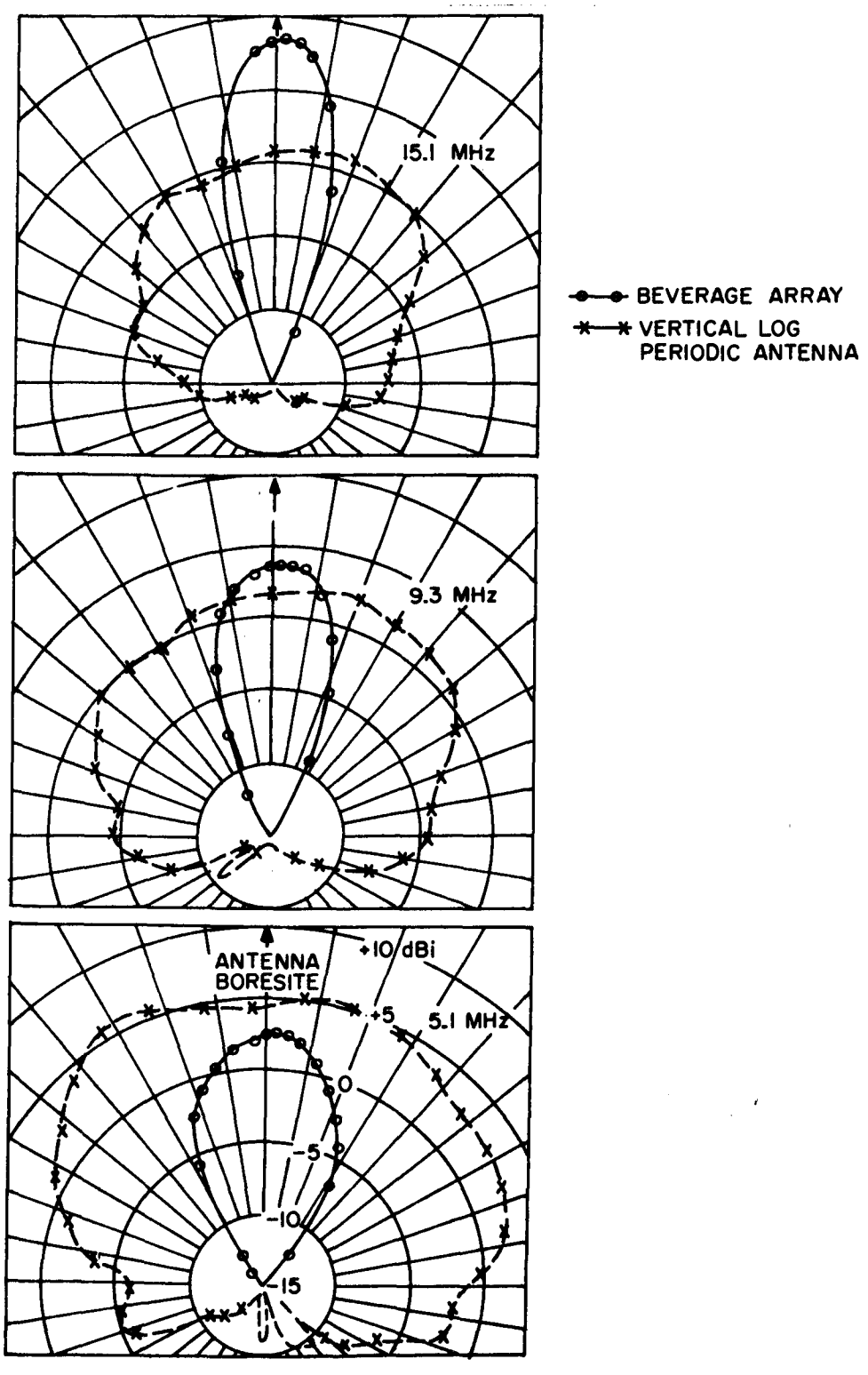


Figure 9b. Measured azimuthal patterns in dBi, at 5.1, 9.3, and 15.1 MHz for the experimental Beverage array, and a nearby vertical log-periodic (Granger model 747V).

Also shown on Figure 9 are the gains found for the nearby vertical log-periodic antenna. Like the transmitting Beverage array, the vertical log-periodic antenna is a broad-band HF antenna intended for use in long-range communications, but it is several times more expensive to construct. The low-angle gain was found to be higher for the experimental Beverage array for all but the lowest frequency, while the directivity was higher at all frequencies. It should be noted, in addition, that this Beverage array was not designed for optimum gain and directivity; a more optimum design is described later in this report.

Figure 10 compares the observed gains, as a function of elevation angle, with those expected theoretically. The programs of reference 1 were used to calculate theoretical patterns; the ground constants used were those for a homogeneous ground derived for the test site from the attenuation constant measurements described in section 2.1.2. The patterns thus calculated were then corrected for inter-element interactions, using the curves of Figure 7 and a mean separation of 5.5 m. The resulting theoretical gain curves are seen to agree well with the observed values, at elevation angles below 20°. At higher angles, the observed gains are less than the theoretical values. This discrepancy is most pronounced at the highest frequency.

The high-angle discrepancy between observation and theory is thought to be due to destructive interference between multiple ground reflections that result from a multi-layered earth. Such interference would be most pronounced at high elevation angles, and high frequencies.

The observed azimuthal patterns were similarly compared with theoretical patterns. In all cases they were found to be in agreement.

2.4 AN OPERATIONAL ARRAY

An operational transmitting Beverage array was installed in November, 1976, for use in a DND communications circuit between Matsqui, B.C., and New Zealand. Transmitter power was 10 kW.

Figure 11 is a plan view of the array. A compromise was made between the aperture size (and therefore the minimum allowable beamwidth) and the gain in the forward direction.

In order to use the 1:4 power dividers effectively, it was considered preferable to restrict the number of elements to a power of 4, or at worst a power of two. The physical aperture was limited by the beamwidth required for reliable point-to-point communications; it was considered that a beam-width at 10° at the 3- dB points was necessary to accommodate off-great-circle modes of propagation. This resulted in the requirement that the aperture be less than 100 m. As it had been shown (section 2.2.1) that an element spacing of 6 m was near optimum, it was decided to use 16 elements, with a 20 foot (6.1 m) spacing for a total aperture of 320 feet (97.5 m). Relatively long (244 m) elements were used to restrict the radiated energy to low elevation angles, and to reduce the power demands and reflections for the termination resistance by virtue of a more attenuated current wave at that end. An antenna height of 7 feet (2.13 m) was selected as a compromise between ease of installation and maintenance, and single-element gain.

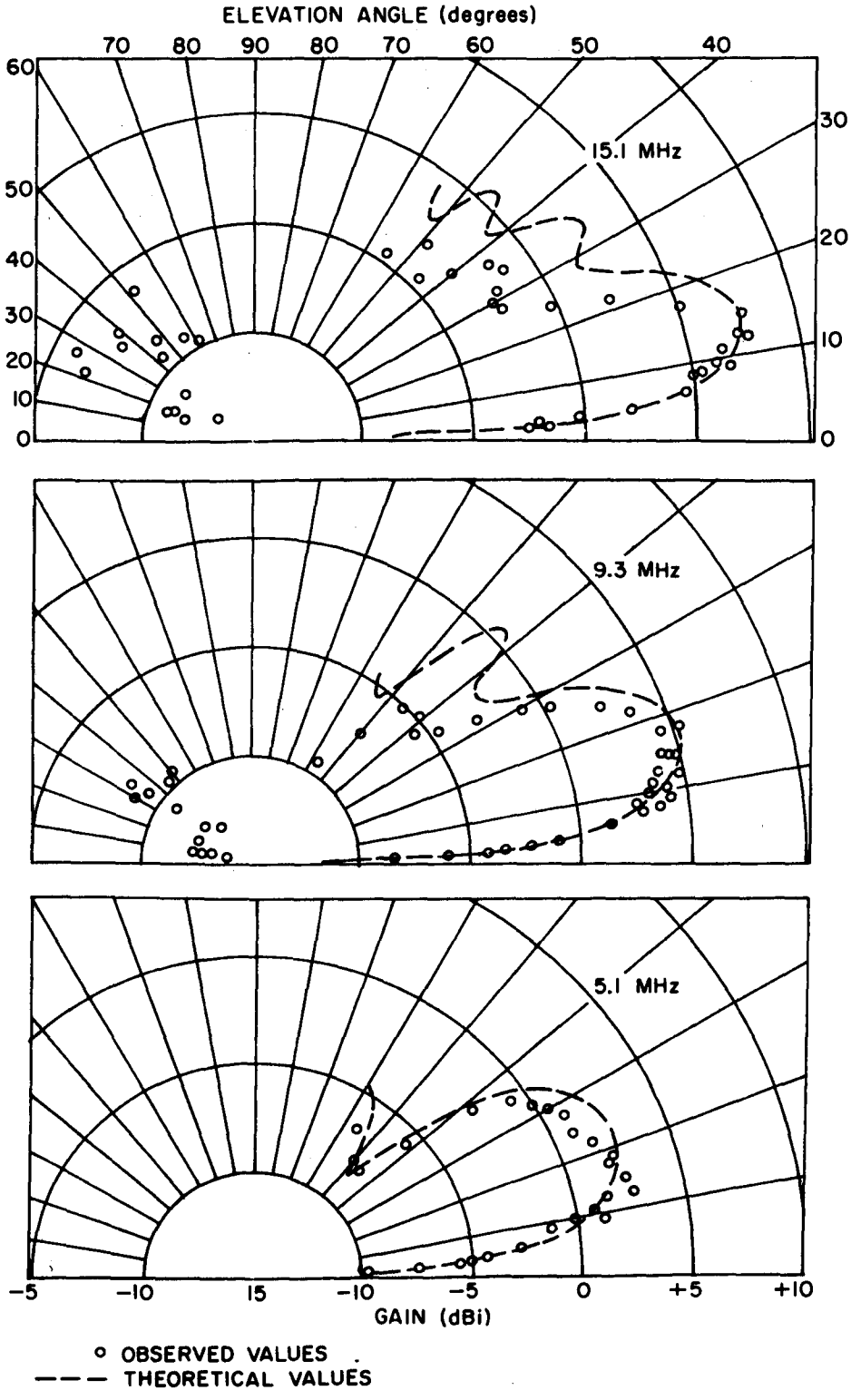


Figure 10. Measured and theoretical elevation patterns in dBi, at 5.1, 9.3, and 15.1 MHz, for the experimental Beverage array.

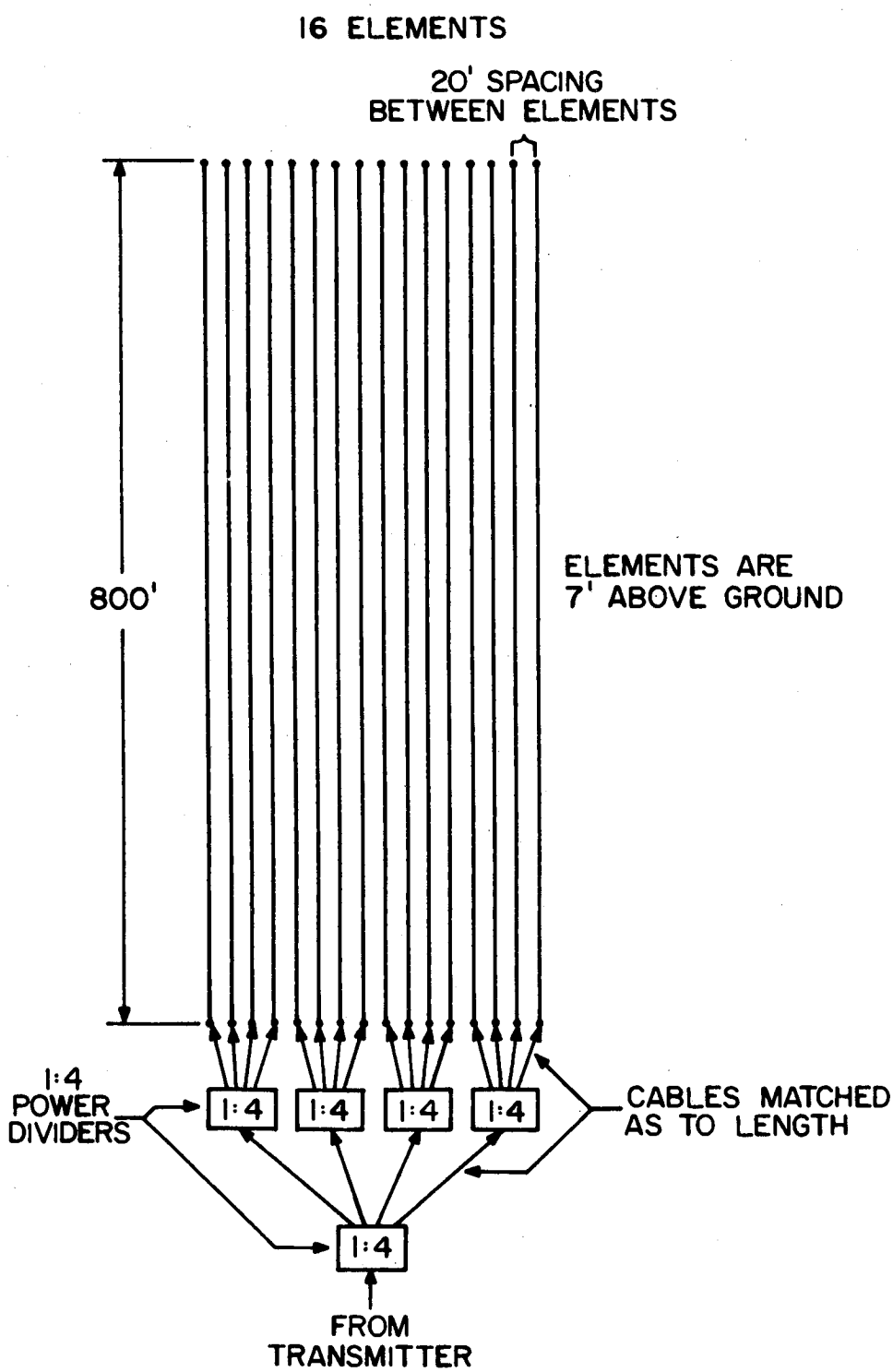


Figure 11. Plan view of the prototype operational transmitting Beverage antenna array at Matsqui, B.C.

Figure 12 shows photographs of the various components used in the array. Components used were required to meet DND requirements for ruggedness and durability. Total cost including all array components, testing and necessary travel, but not including labour was less than $15,000.

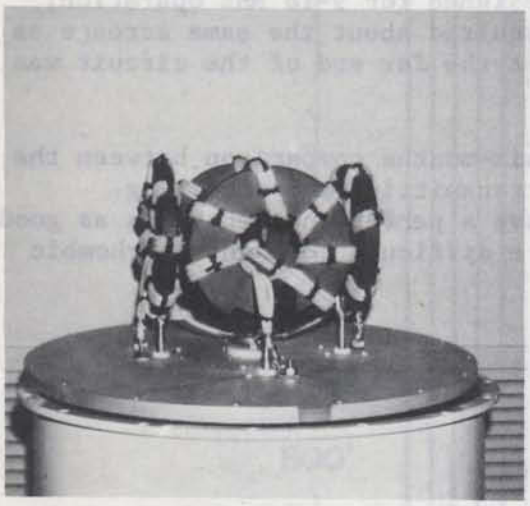
The performance of the array in teletype communications was compared against that of an already-existing rhombic antenna that had been designed for the circuit. The rhombic antenna was designed for 9-18 MHz operation; it has a height of approximately 25 m and required about the same acreage as the Beverage array. The receiving antenna at the far end of the circuit was also a rhombic antenna.

Table 3 summarizes the results[6] of a six-months comparison between the two antennas. In spite of the non-similar transmitting and receiving antennas, the Beverage array was found to have a performance that was as good as the more costly, less broad-band, and more difficult to maintain rhombic antenna.

TABLE 3

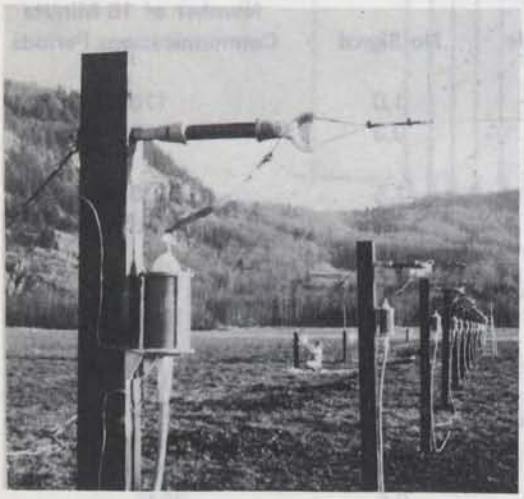
Results of a Comparison Between the Matsqui, B.C. Transmitting Beverage Array and a Rhombic Transmitting Antenna, for Communications to New Zealand[6].

		Percentage of Times that Communications Was Judged to be:			
Frequency	**Antenna**	**Suitable**	**Not Suitable**	**No Signal**	**Number of 15 Minute Communications Periods**
6 MHz	Beverage	58.9	40.1	1.0	170
	rhombic	47.0	52.7	0.3	270
9	Beverage	59.5	39.0	1.5	1130
	rhombic	71.0	28.7	0.3	1228
11	Beverage	68.4	32.4	2.8	1119
	rhombic	59.0	38.3	2.7	1048
13	Beverage	80.4	19.6	0.0	179
	rhombic	60.6	37.1	2.3	202
15	Beverage	91.8	7.7	0.5	1845
	rhombic	92.7	6.8	0.5	2045
17	Beverage	93.4	6.6	0.0	327
	rhombic	83.6	12.3	4.1	336
All frequencies	Beverage	77.9	20.8	1.3	4851
	rhombic	77.3	21.3	1.4	5105

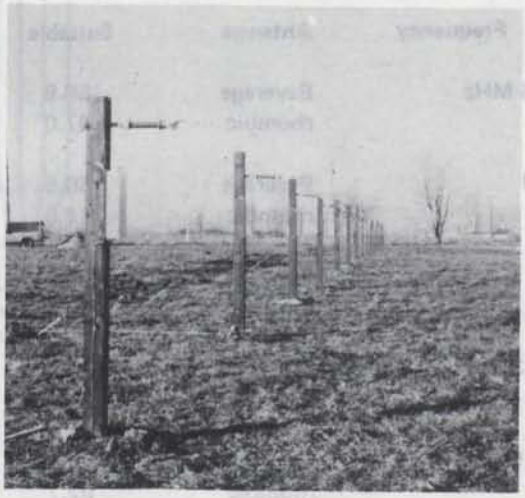


10 kW 1:4 Power Divider Assembly and Case

1:4 Power Divider in Place



Matching Transformers at Feed End



Terminating Resistors in Housings

Figure 12. Components in use in the prototype transmitting array at Matsqui, B.C.

3. RECOMMENDATIONS

The Beverage antenna's utility as an HF receiving device is well documented in reference 1. The work contained in the present report has concentrated mostly on its use as an HF transmitting device; the following recommendations result:

1. The Beverage antenna can be adopted for use as an HF transmitting antenna, notwithstanding its low efficiency, by placing parallel elements in arrays. Such arrays can be configured to be many times more efficient than a single element, with forward gains that are comparable to or better than other broad-band antennas currently in use in long-range communications systems. This result, along with the previously established features of Beverage antenna arrays, such as high directivity, good low-angle response, low cost, and ease of maintenance, makes the Beverage antenna array attractive for both transmitting and receiving in long range point-to-point HF communications systems.

2. The increase in efficiency that can be achieved by adding elements to a Beverage array is ultimately limited by the interactions between elements becoming greater as the spacing is reduced. The reduction in gain due to these interactions was found to be slightly frequency dependent over the HF spectrum. The gain achievable by adding elements within a fixed physical aperature is illustrated in Figure 7 of this report, for a 1.8 m antenna height, and ground conditions that may be described as poor to average. At spacings of less than 6 m, interactions appear to remove most of the increase in gain expected through the addition of extra elements. The characteristic impedance of individual elements, however, is not so quickly affected as the spacing is reduced; impedance effects become significant only at spacings less than 2 m for the above conditions.

   Antenna heights of the order of 2 m were found to be appropriate for most HF transmitting applications. For these heights, we recommend an inter-element spacing of the order of 6 m, as being a reasonable compromise between maximum array efficiency and cost.

3. The theory developed for non-interacting Beverage arrays in reference 1, when combined with a constant (measured) direction-independent reduction in gain presumably resulting from interactions, was found to be adequate to describe the antenna patterns of Beverage arrays at elevation angles below 20°. Above this figure, the observed gains were less than predicted by theory, especially at the higher HF frequencies. This discrepancy was most likely due to the existence of a layered ground causing a series of reflected waves which interfered destructively at the higher angles. Therefore, the theoretical predictions of reference 1, coupled with the measured interaction effect (Figure 7) can be used to predict the gains of Beverage arrays of the order of 2 m height, for elevation angles less than 20°. These are the angles of importance to long-range communications. At higher angles, there may be a lower observed gain than expected, if the ground contains several layers within a few meters of the surface.

4. The attenuation length, for current in the Beverage antenna, was observed to be strongly frequency dependent. At the 1.8 m height, and poor-to-average soil conditions, it is recommended that the length be kept above 150 m, to make efficient use of the current wave. However it is not necessary to go beyond 250 m, as the current wave will be well attenuated by then.

5. The grounding technique was determined to be important, not only because of the ground coupling required for this type of antenna (which makes use of ground currents), but also because of the importance of achieving the constant, real characteristic impedance necessary for good matching at all HF frequencies. A broad, three-strap grounding configuration (Figure 4a, configuration 3) was determined to be the best of the various techniques tested; it is more than adequate for most transmitting applications.

6. For point-to-point communications, an azimuthal beamwidth of the order of 10° or more was considered necessary. This consideration, along with the above results on spacing and height, resulted in the development of a 16-element, 6 m-spacing linear transmitting array of 2 m-high, 150 to 250 m-long Beverage antenna elements. We recommend this configuration for moderate-cost long-range point-to-point HF communications applications. The gain parameters for such an array, over poor-to-average soil are listed in Table 4 below.

TABLE 4

Calculated Gain Parameters, Including Interaction Effects, for a 16-Element, 6 m spacing Linear Array of 2 m High, 200 m Long Beverage Antenna Elements.

Frequency (MHz)	5	10	15 MHz
Maximum gain (dBi)	7	9	11
Elevation angle of maximum	19°	15°	13°
Elevation beamwidth*	23°	17°	14°
Azimuthal beamwidth*	30°	15°	10°

* at 3 dB points

4. REFERENCES

1. Litva, J. and B.J. Rook, *Beverage Antennas for HF Communications, Direction-Finding and Over-the-Horizon Radars*, CRC Report No. 1282, 1976.

2. Alexanderson, E.F.W., *Trans-Oceanic Radio Communication*, Proc. IRE, Vol. 8, pp 263-285, 1920.

3. DeSantis, C.M., D.V. Campbell and F. Schwering, *An Array Technique for Reducing Ground Losses in the HF Range*, IEEE Trans. Antennas and Propagation, Vol. AP-21, pp 769-773, 1973.

4. J. Reynolds, personal communication.

5. Moss, G.E., N. Muirhead, W.E. Thompson, A. Whitford, and R.W. Jenkins, *An Aircraft-Borne System for the Measurement of HF Antenna Patterns*, currently being prepared for publication.

6. J. Sydor, personal communication.

APPENDIX A

1:4 POWER DIVIDER

The 1:4 power divider divides the power fed to its input port, equally and in phase to four output ports, each having the same impedance as the input port.

It consists of four bifilar-wound auto-transformers with a 2:1 turns ratio, wound on separate powdered iron toroidal cores. The primary windings of the four transformers are connected to a common input port and ground, and the secondary windings of each transformer are connected to four separate output ports. In this way the impedance of each output port remains the same as that of the input port, the power at each output port is one-quarter that at the input port, and the phase relationship between input and output is the same for all output ports.

Versions of this power divider capable of handling in excess of 10 kW input power over the HF band have been constructed and are currently in use. This type of divider network is registered under *Canada Patent Number 271563*.